Concept of Operations for a Prospective "Proving Ground" in the Lunar Vicinity

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***Abstract*—NASA is studying a "Proving Ground" near the Moon to conduct human space exploration missions in preparation for future flights to Mars. This paper describes a concept of operations ("conops") for activities in the Proving Ground, focusing on the construction and use of a mobile Cislunar Transit Habitat capable of months-long excursions within and beyond the Earth-Moon system. Key elements in the conops include the Orion spacecraft (with mission kits for docking and other specialized operations) and the Space Launch System heavy-lift rocket. Potential additions include commercial launch vehicles and logistics carriers, solar electric propulsion stages to move elements between different orbits and eventually take them on excursions to deep space, a node module with multiple docking ports, habitation and life support blocks, and international robotic and piloted lunar landers. The landers might include reusable ascent modules which could remain docked to in-space elements between lunar sorties. The architecture will include infrastructure for launch preparation, communication, mission control, and range safety. The conops describes "case studies" of notional missions chosen to guide the design of the architecture and its elements. One such mission is the delivery of a ~10-ton pressurized element, co-manifested with an Orion on a Block 1B Space Launch System rocket, to the Proving Ground. With a large solar electric propulsion stage, the architecture could enable a year-long mission to land humans on a near-Earth asteroid. In the last case, after returning to near-lunar space, two of the asteroid explorers could join two crewmembers freshly arrived from Earth for a Moon landing, helping to safely quantify the risk of landing deconditioned crews on Mars. The conops also discusses aborts and contingency operations. Early return to Earth may be difficult, especially during later Proving Ground missions. While adding risk, limited-abort conditions provide needed practice for Mars, from which early return is likely to be impossible.**

TABLE OF CONTENTS

1. INTRODUCTION

NASA is studying conceptual architectures for a "Proving Ground" near the Moon or in high lunar orbit to conduct human space exploration missions to help bridge the gap between today's operations with the International Space Station and future human flights to Mars beginning in the 2030s [1]. Following established practices, the study team is simultaneously developing conceptual designs, a set of top-level requirements, and a concept of operations ("conops"). The conops is a narrative that tells what mission element performs which mission activity at what time. As a project proceeds through its development cycle, the conops evolves in parallel with the system design and the requirements, informing both and changing in response to both. Companion papers presented at this conference discuss several different aspects of the Proving Ground. This paper focuses on the conops. It briefly describes the flight and ground elements that comprise the architecture, summarizes the missions flown under its purview, and provides step-by-step operational sequences for a representative subset of those missions. It covers a few aspects of aborts and contingency operations. The paper concludes with a short summary and a discussion of future directions for the study.

2. FLIGHT ELEMENTS

Flight elements—rockets and spacecraft—are the "actors" in space operations. This section describes the flight elements currently under study for the Proving Ground.

Space Launch System Heavy-Lift Rocket

First among the architecture's flight elements is the Space Launch System, an evolvable heavy-lift launch vehicle [e.g., 2]. Its initial configuration, called Block 1, includes a Core Stage with four RS-25D engines that burn liquid oxygen and liquid hydrogen, plus two five-segment solid rocket boosters. Block 1 can deliver up to 70 metric tons into a -87 × 241 km low Earth orbit. That mass allowance encompasses an Orion spacecraft (or equivalent cargo) along with an Interim Cryogenic Propulsion Stage powered by a single RL-10 engine for in-space propulsion.

The first planned upgrade of the Space Launch System is called Block 1A. It replaces the solid rocket boosters with advanced boosters that increase the rocket's low Earth orbit capability to 105 tons. The addition of a new upper stage to Block 1A defines Block 2, with a low Earth orbit capability of 130 tons. Alternative upgrade options are under consideration. A proposed Block 1B uses an Exploration Upper Stage with four RL-10 engines to reach the 105 ton benchmark without advanced boosters.

Some elements of the Proving Ground will be so large that they can only fly on the Space Launch System. This study assumes that Block 1B will be available for piloted missions following the Exploration Mission 2 test flight. Block 1B can carry an Orion spacecraft and an additional co-manifested payload of about 10 tons through trans-lunar injection. Much of the Proving Ground architecture, which we describe below, is built with these 10-ton elements.

Orion Spacecraft with Mission Kits

The next key element is the Orion spacecraft [e.g., 3], which provides flight controls, a habitable environment, and crew accommodations for four people for missions as long as 21 days, enabling meaningful missions beyond low Earth orbit. Somewhat longer missions are possible with only two crew members. Future upgrades may increase the crew complement to six.

The Orion consists of a Crew Module where the crew live and work; a Service Module with engines, solar arrays, batteries, thermal radiators, and storage for consumables; a Launch Abort System for pad and ascent emergencies; and a Spacecraft Adapter to connect the Orion to the launch vehicle. The basic Orion is not equipped for rendezvous, docking, or spacewalks. It needs supplemental mission "kits" for flights that include those activities.

The Orion system includes flight suits to protect the crew for launch, entry, and serious failures such as loss of cabin pressure. Although it can tolerate vacuum, the Orion flight suit is designed to be a survival suit, not a spacewalking suit: it can provide contingency capability for emergency repairs in space, but will require additional upgrades to be acceptable for planned microgravity spacewalks, such as those envisioned for human exploration of an asteroid.

The Orion vehicle and flight suit provide basic life support for the crew. Food, clothing, and everything else that the crew needs during a mission are not considered part of the Orion system and are the responsibility of a separate organization.

International Space Station

The International Space Station is not formally a part of the Proving Ground, but it will serve as a testbed for equipment, operational techniques, and possibly entire modules (see "Advanced Life Support Module" below) that will be employed there.

Small Power and Propulsion Bus

The first element to arrive in the Proving Ground is a robotic spacecraft that can provide electrical power and orbit maintenance for the modules that will follow, some of which may not have those capabilities themselves. This approach substantially reduces the architecture's total mass by eliminating the need for every element to be able to fly on its own, and it improves the architecture's resilience by allowing later elements to launch in any order. We envision the small power and propulsion bus launching with Orion as a co-manifested payload and flying to its destination along with the crew.

The development time frame of the Proving Ground overlaps that of the proposed Asteroid Redirect Mission. A 10-ton spacecraft similar to the conceptual Asteroid Redirect Vehicle—with 50 kW solar arrays, a 40 kW electric propulsion system, and 5 tons of propellant storage—could capably serve as the initial power and propulsion bus for the Proving Ground. The bus would use gimbaled Hall effect xenon thrusters. Its propulsion system would include a propellant feed system, power processing and switching, thermal management equipment, and navigation and flight control hardware and software. The vehicle would also carry a communication system, an attitude determination and control system, core bus components, and a standardized fixture allowing other elements to dock with it.

Small Habitat

The small habitat is a candidate for the next element to arrive after the small power and propulsion bus. It provides the functions to maintain a crew of four on missions longer than the Orion can support alone. It depends on the small power and propulsion bus for energy, attitude control, and orbit maintenance, but includes systems for communication, thermal management, power storage and distribution, command and data handling, air circulation, crew exercise, cabin lighting, caution and warning, and docking of one or more additional spacecraft. As currently envisioned, the small habitat also serves as the base for a robotic manipulator arm, with crew controls inside the cabin. The small habitat may contain a single pressurized volume, or include separate airtight compartments for transfer functionality. Life support functions beyond basic air circulation are provided by the docked Orion.

The small habitat launches with an Orion as a co-manifested payload, which constrains its mass to no more than 10 tons. After trans-lunar injection, Orion docks to the small habitat and separates it from the Exploration Upper Stage. Orion provides attitude control for the mated stack and pushes the small habitat through a lunar swingby, an insertion burn at the destination orbit, and a rendezvous and docking with the small power and propulsion bus.

Advanced Life Support Module

The Proving Ground may include a module dedicated to testing advanced regenerative life support systems. In some development scenarios, this module travels to the International Space Station where its systems receive a thorough shakedown. It then moves to the Proving Ground to provide life support services for long crewed stays and excursions.

Small Node

Another early-arriving element is a node that provides additional habitable volume and at least three docking ports: one for an Orion, one for a visiting logistics carrier, and one for further expansion of the stack. Additional docking ports (for an additional visiting vehicle or an airlock) may be desirable and are the subject of ongoing trade studies.

Like the small habitat, the node is a 10-ton payload launched in conjunction with an Orion. It is equipped for communication, rendezvous and docking, command and data handling, power distribution and storage, thermal control, atmosphere conditioning, cabin lighting, and caution and warning annunciation.

Two options for node's form factor are currently under study. One possibility is a cylinder with radial and axial ports, superficially similar to an International Space Station node. Another option is a sphere with up to six ports, like a scaled-up version of the docking nodes at the forward ends of the Space Station's Service Module and Functional Cargo Block.

Logistics Carriers

The Proving Ground architecture is open to robotic cargo spacecraft to deliver consumables such as food, water, and propellant, and to remove trash. These spacecraft must include complete power and propulsion systems. A variety of existing and future commercial and international vehicles, which future work will identify, may participate. Alternatively, a 10-ton logistics carrier (with or without its own power and propulsion) could be co-manifested on an Orion flight.

Commercial and International Partner Launchers

Besides the Space Launch System, the Proving Ground architecture is open to other commercial and international launch vehicles such as Ariane, Atlas, Delta, and Falcon 9 Heavy, especially for logistics resupply. Future studies and agreements will determine which additional launchers might participate in the Proving Ground.

Large Habitat

The large habitat, delivered midway through the Proving Ground buildup, is designed to enable piloted missions of longer duration. Its 20-ton mass exceeds the capability of a commercial launcher or a co-manifested payload on an Orion flight. Launching this element requires a cargo-only configuration of the Block 1B Space Launch System. We envision that the large habitat will fly together with the large power and propulsion bus (see below), which together match the payload capability of a Block 1B cargo rocket.

The large habitat provides a platform to prove out the regenerative life support system capabilities that are necessary to bring the logistics needs of a Mars mission within reasonable bounds. These functions include removal of carbon dioxide from cabin air, production of oxygen from carbon dioxide and water, purifying wastewater and cabin air condensate to make drinking water, and scavenging water from urine. The large habitat includes additional crew accommodations for long-duration flights: a maintenance workstation, laundry facilities, a food freezer, a second toilet (in addition to the one on Orion), and a galley with a food warmer and a hot water dispenser. Like the other flight elements, the large habitat is equipped for thermal control, rendezvous and docking, command and data handling, distribution and storage of electrical power, and caution and warning.

Large Power and Propulsion Bus

Later missions to the Proving Ground may take the habitable stack and its crew out of lunar orbit for shakedown missions toward, or beyond, the boundary of the Earth's sphere of influence (about 1.5 million km). These missions will add challenge and verisimilitude in preparation for later flights to Mars. Moving the large habitat and other accompanying elements will require a powerful in-space propulsion stage.

We envision a large power and propulsion bus with both solar-electric and chemical engines. The electric propulsion component has 190 kW solar arrays, a 150 kW Hall effect propulsion system, and 16 tons of xenon propellant. The chemical propulsion system could use monomethyl hydrazine and nitrogen tetroxide, methane and liquid oxygen, or other propellants. Trade studies to identify the best choice are presently underway.

Robotic Lunar Landers

During the 2020s, the United States and other spacefaring nations are likely to be conducting vigorous robotic exploration of the Moon. The Proving Ground architecture may provide valuable capabilities for crew teleoperation of lunar rovers in locations not visible from Earth (e.g., the geologically interesting South Pole-Aitken basin, and ice-rich permanently shadowed craters near the poles), for crew-assisted transfer and return of robotically collected lunar samples, and for reusable lunar landers to dock at a human-tended facility between sorties. Future work will identify how the Proving Ground might cooperate with robotic exploration and resource development on the Moon.

Optional International Lunar Landers

Current space exploration policy in the United States does not favor landing astronauts on the Moon's surface, but other nations' space agencies are much more interested. One possible area of synergy is a reusable, refuellable international partner lunar ascent module that would reside at the Proving Ground when not in use for a lunar sortie. Such a module would necessarily include an airlock for lunar spacewalks, and could therefore be used for spacewalks on the Cislunar Transit Habitat while docked there.

3. SUPPORTING ELEMENTS

Flight hardware cannot execute a space mission by itself. The additional elements that support Proving Ground missions are launch site infrastructure, communication and tracking assets, mission control centers, and Range Safety.

Launch Site Infrastructure

NASA's human spaceflight directorate charters the Ground Systems Development and Operations program to provide infrastructure and services to process, launch, and recover flight elements. Its assets at Kennedy Space Center in Florida include the mobile launcher, crawler transporters, component processing facilities, vertical and horizontal assembly facilities, firing rooms, and launch pads, along with the ancillary facilities that support them. The program also provides services such as motion imagery and end-to-end command and control. Crew recovery after landing is another important function of the Ground Systems program.

Communication and Tracking Assets

The communication architecture transmits commands, telemetry, voice, video, and other mission data. It operates during launch, entry, aborts, post-mission recovery, and in-space operations, to support mission activities, scientific research, public outreach, failure analysis, and certification of flight elements. It includes the following key assets:

• Space Communications and Navigation Network launch head facilities and other ground tracking stations which coordinate with the Eastern Range to provide communications and tracking during ascent.

• The Tracking and Data Relay Satellite System (TDRSS), which tracks and communicates with spacecraft in low Earth orbit. Additional tracking-only assets can augment TDRSS communication-link tracking as needed. The TDRSS network provides communication and tracking services for vehicles within ~30,000 km of Earth. More distant vehicles must communicate via other assets.

• The Deep Space Network and potential future assets near the Earth and in deep space for communication with spacecraft beyond low Earth orbit.

• Potential future relay satellites for communications, tracking, and networking on multi-element exploration missions.

• Communication and tracking capabilities among future exploration spacecraft, which could include radar, lidar, and communication-link radiometric techniques for relative navigation functions and point-to-point communication services.

• The NASA Integrated Services Network, which provides terrestrial communication lines among NASA centers and between NASA and Eastern Range facilities.

Mission Control

Mission control centers plan space flights, train flight controllers and crews, and command, control, track, navigate, and monitor spacecraft in flight. They have real-time command and control responsibility beginning at first motion and continuing through end of the mission, when they hand operations over to recovery assets. NASA's mission control facilities include:

• The Mission Control Center located at Johnson Space Center in Houston, Texas. Mission Control commands, controls, and monitors the International Space Station and other spacecraft that carry crew. It includes flight planning functions. It interfaces with the United States Department of Defense and with the communication infrastructure (see above).

• Simulators and mockups to train crew members and flight controllers and to provide engineering evaluation environments for operations planning, command and telemetry verification, procedure validation, and flight system troubleshooting.

• Software and processes to support mission training and real-time mission operations, and to create flight design products, mission timelines, flight rules, flight and ground procedures, and other related products.

A key goal of the Proving Ground is to demonstrate human operations in deep space with reduced reliance on Earth. Today, NASA employs a staff of 6-35 people working around the clock to operate the International Space Station in real time. This works well for the near-continuous, low-latency, high-bandwidth communication link that the Space Station enjoys. But research suggests that this model will break down when communication gaps become common, or when the round-trip communication delay exceeds about 10 seconds (corresponding to the Earth-Sun Lagrange-1 and -2 points). Mission control centers must develop new capabilities to operate with intermittent, delayed, and reduced-bandwidth communication. One such capability is a division of responsibility between flight and ground elements that adapts to variable communication states. Others include text messaging to supplement voice, store-and-forward data transmission, disruption-tolerant networking, and the ability to control multiple piloted vehicles at once.

While Mission Control Houston will provide flight control services for piloted American spacecraft at the Proving Ground, other elements, such as robotic cargo and service ships and partner-provided landers for human lunar surface sorties, will probably be operated from their own separate but interconnected control centers across the United States and around the world.

Range Safety

Rocket launches may create hazards such as explosions, debris, uncontrolled vehicles, and toxic releases. At the Eastern Launch and Test Range, where most Proving Ground missions will start, protecting people and property on the ground from launch hazards is the joint responsibility of NASA (the range user) and the 45th Space Wing of the United States Air Force (the range owner and operator).

The Air Force has regulatory accountability for safety at its launch ranges. It approves launches and supports the 1st Range Operations Squadron's flight control function. It evaluates launch and flight risks, issues Notices to Airmen, and establishes vehicle destruct criteria. It also provides occasional reviews and feedback to aid NASA in developing the products required for flight plan approval.

While preparing for Air Force launch approval, NASA also develops independent mission rules, system and flight safety analyses, and Flight Termination System assessments to meet its own requirements.

4. Development Scenario

Activities in the Proving Ground pave the way for human exploration of Mars by building up a spacecraft capable of sustaining crews for many months, then taking that spacecraft on excursions through, and later away from, the Earth-Moon system. The study team has proposed a set of development scenarios that build the spacecraft in a logical sequence, tolerate delays and changes in the launch order of its components, provide adequate logistics traffic, respect projected budgets and Space Launch System flight rates, provide engaging flight activities each year, accommodate participation from commercial and international partners, and execute exploration missions of increasing range and difficulty that culminate in a voyage comparable to a Mars transit. Many different mission orderings satisfy those requirements. In this paper, we present "Scenario 4," one of several options the study team developed. Figures 1a and 1b illustrate Scenario 4 graphically. The following paragraphs describe the scenario step by step.

The Proving Ground scenario begins after the two planned test flights of the Orion spacecraft: the uncrewed circumlunar Exploration Mission 1 in 2018, and the piloted circumlunar Exploration Mission 2 scheduled for 2021. The latter mission is illustrated on the far left of Figure 1a.

In 2022, Exploration Mission 3 launches on a Block 1B Space Launch System rocket with an Orion spacecraft and the small power and propulsion bus. They travel to a "near-rectilinear" polar lunar orbit (NRO) with a period of about 11 days, a 4000-km altitude perilune over the Moon's north pole, and a 73,000-km altitude apolune over the south pole. Such an orbit precesses once a month so that the normal to the orbit plane always points toward Earth, and the Moon never occults the spacecraft. It also affords long hang times over the south pole for teleoperation of scientific or prospecting robots in that region. Because the four-person crew must rely on Orion for their life support needs, they can only remain in the destination orbit for a day or two before undocking from the small power and propulsion bus and returning to Earth.

In 2023, Exploration Mission 4 launches with an Orion and the small habitat. It travels to NRO and docks the habitat to the waiting power and propulsion bus. From this point forward, the combined spacecraft (including all elements added on later flights) is called the Cislunar Transit Habitat. Using logistics carried in the habitat, the crew of four astronauts can remain for up to 45 days before undocking their Orion and returning to Earth.

Also in 2023, a medium launch vehicle delivers the Advanced Life Support Module to the International Space Station. The module remains docked to the Space Station for about two years while its life support systems are thoroughly tested.

Exploration Mission 5 launches in 2024 with an Orion and the small node. It docks to the open axial port on the habitat. Using logistics stowed in the node, the crew remains for up to 60 days before undocking and returning to Earth.

The year 2025 sees the launch of a robotic lunar sample return mission on a medium-lift rocket. The robot may collect scientific specimens, samples of extractable resources, or both. When the sample return vehicle is ready to leave the Moon, a crew flies to the Proving Ground on a partner vehicle (possibly a Russian Crew Transfer Vehicle launching on an Angara rocket). The sample return robot launches from the Moon and flies to the Cislunar Transit Habitat, where it docks to a fixture providing power, data, and a releasable mechanical interface. The crew members secure the sample container and transfer it to their vehicle for undocking and Earth return. The first of two Space Launch System flights in 2025 is the inaugural mission of the Block 1B cargo configuration. It brings the large habitat and the large power and propulsion bus, which dock to the stack without flight crew interaction.

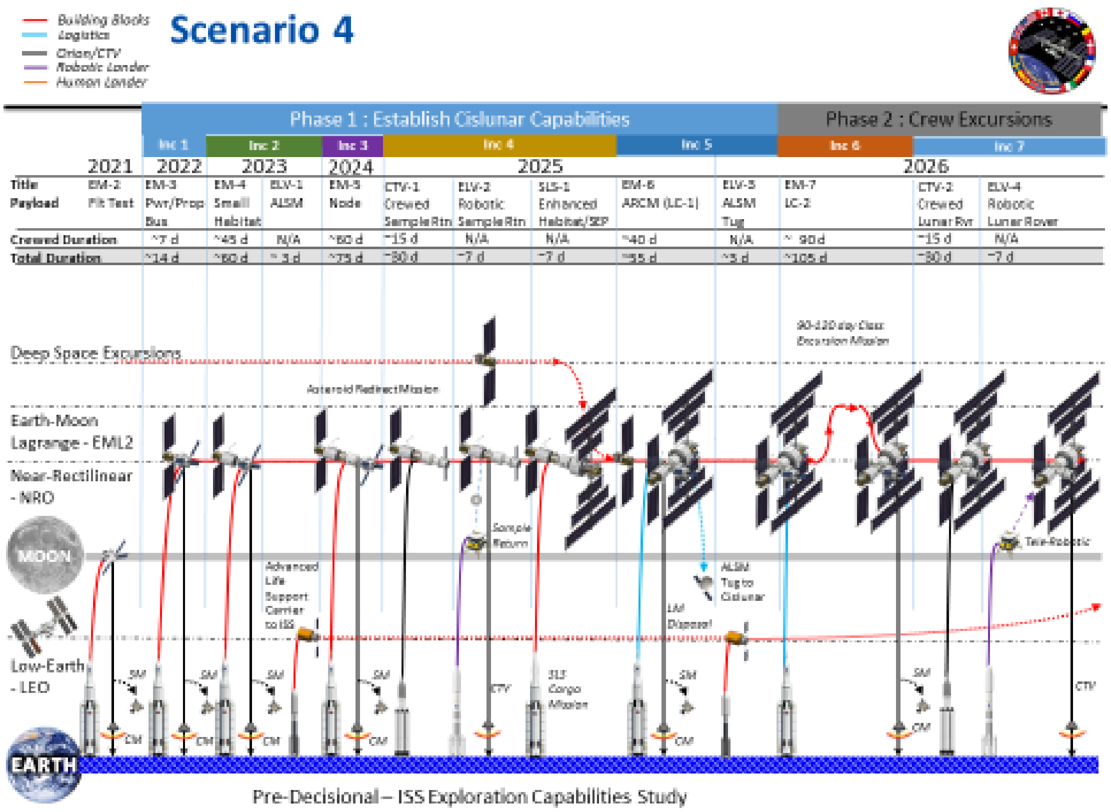

Figure 1a. Notional Proving Ground development scenario, part 1 (2021-2026).

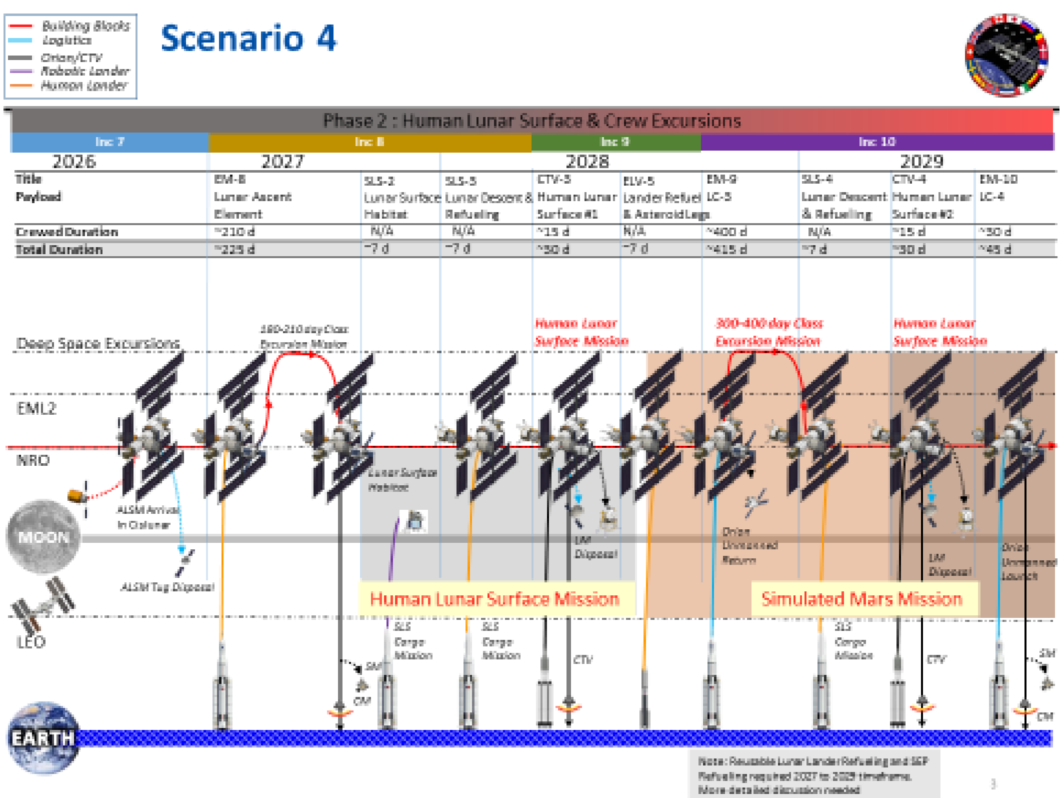

Figure 1b. Notional Proving Ground development scenario, part 2 (2026-2029).

Also in 2025, the Asteroid Redirect Mission spacecraft is scheduled to return to the Earth-Moon system with a boulder captured from the surface of an asteroid. In this scenario, it meets the Cislunar Transit Habitat in lunar orbit and docks with it. Exploration Mission 6 is the Asteroid Redirect Crew Mission: an Orion with a co-manifested logistics carrier containing spacewalking suits and geological sampling equipment. With the benefit of proper suits, extensive tool kits, and a large, capable ship with plenty of supplies, the crew can remain for 40 days and conduct up to a dozen 6-hour spacewalks to completely characterize the boulder. This represents a great improvement over the two 4-hour spacewalks in marginally operable suits as originally envisioned for this mission. At the close of the mission, the crew undocks with the asteroid samples in the Orion crew module. They take the used logistics carrier with them for disposal.

In 2026, a medium launch vehicle carries a solar-electric tug to the International Space Station, where it docks to the Advanced Life Support Module. The tug takes about one year to carry the module out to the Proving Ground.

Exploration Mission 7 launches later in 2026 with a logistics carrier that contains supplies for a 120-day excursion mission. After Orion docks to the Cislunar Transit Habitat, the large power and propulsion bus begins to adjust its orbit. Several options are possible, including a stay in polar Earth orbit at roughly lunar distance. The large habitat sustains the crew for this lengthy trip. Orion provides abort capability for early mission termination throughout the flight profile. At the end of the excursion, the stack returns to lunar orbit. The crew undocks with the spent logistics carrier and returns to Earth.

Also in 2026, an international partner crew may launch on a Crew Transfer Vehicle to stay in the habitat for several weeks and teleoperate a separately-launched robotic lander or rover on the Moon's surface.

The final major event of 2026 is the arrival of the Advanced Life Support Module at the Proving Ground, as illustrated on the far left of Figure 1b. After docking, the tug separates and enters a disposal orbit.

In 2027, Exploration Mission 8 launches with a co-manifested element still under study (possibly a partner-provided reusable lunar ascent module). After the Orion docks to the Cislunar Transit Habitat, the stack departs lunar orbit for a 210-day excursion. Destination options for this trip include an Earth-Sun Lagrange-1 or -2 point, or a near-Earth asteroid flyby. Portions of this excursion are likely to exceed Orion's abort capabilities. This adds risk incrementally with the goal of proving systems and operational methods for a Mars flight, during which aborts will be generally impossible. When the stack returns to lunar orbit, the Orion returns the crew to Earth for another important milestone for Mars risk reduction: subjecting deconditioned long-duration crew members to interplanetary re-entry stresses.

Additional international exploration missions in the Earth-Moon system may be carried out in the Proving Ground during 2027 and 2028 if appropriate partner-provided spacecraft and NASA Space Launch System cargo flights are available. Scenario 4 accommodates a cargo launch that takes a partner-provided habitat to the surface of the Moon, a second cargo launch that brings a partner-provided lunar descent stage to the Proving Ground, and a Crew Transfer Vehicle that carries a multinational crew for a lunar surface sortie.

The year 2028 sees the launch of a partner-provided logistics module (possibly including fuel for the reusable lunar ascent module and equipment for docking with an asteroid), and also Exploration Mission 9, an Orion with a co-manifested logistics carrier. The crew transfers to the Cislunar Transit Habitat, and their Orion undocks and returns to Earth with nobody on board. Under the same no-abort conditions that a Mars mission will face, the stack departs lunar orbit for an excursion lasting about one year, which we consider the minimum duration to prove systems and operational techniques for a 1,000-day round trip to Mars. A possible destination for the one-year trip is a near-Earth asteroid. The long mission duration, coupled with the propulsive capability of the large power and propulsion bus, is likely to allow a rendezvous with the target object and enough time on station to explore it thoroughly with robotic assets and human spacewalkers.

The stack returns to lunar orbit in 2029. An unpiloted Orion meets it there and docks autonomously, providing crew return capability. If partner-provided capability is available in this time frame, there is the potential to retire another key risk for future Mars landings by flying a second piloted ship (likely a Crew Transfer Vehicle) to the stack and sending a split crew of two deconditioned asteroid explorers and two "fresh" crew members for a landing on the Moon. That mission would also require a Space Launch System cargo launch with a partner-provided lunar descent stage.

5. Pressurized Element Delivery Flight

The Proving Ground conops includes descriptions of notional missions chosen to guide the design of the architecture and its elements. One such "case study" is the first pressurized element delivery flight, which serves as a template for the many missions that use a Block 1B Space Launch System rocket to deliver an Orion and a 10-ton co-manifested payload to the Proving Ground. The flight profile includes a 10-day transit to lunar Near Rectilinear Orbit (with a propulsive lunar gravity assist about 5 days after launch), rendezvous and docking with a power and propulsion bus delivered on an earlier flight, a day or two of docked operations in the destination orbit, and undocking of the Orion followed by a 13-day return to Earth, again with a lunar swingby. A detailed phase-by-phase description of the mission follows.

Mission Planning and Training

Flight planning begins well before launch. Managers prepare for an upcoming mission by incorporating lessons learned from past flights, developing mission requirements and manifests, and setting schedule milestones that allow time for manufacturing and assembly, with reserves in case of unforeseen setbacks.

Engineers, flight controllers, and astronauts prepare for flight by developing flight plans, refining flight rules, and establishing flight techniques. They develop nominal and malfunction procedures and flight and ground data displays. They define abort actions and abort mode boundaries. They test all of the foregoing products in mission simulations, which also serve to train crews and controllers.

Launch Preparations

Preparing rockets and spacecraft for launch is an important, and often overlooked, aspect of space operations. Engineers and technicians at the launch site process, integrate, test, and launch space hardware. Their work includes refining operational concepts to reduce overhead and maintenance, optimizing use of ground assets, training and preparing launch and recovery teams, and recording lessons learned from each launch campaign and using them to improve future operations.

Each piece of flight hardware arrives at the launch site, where its manufacturer formally turns it over to the launch site authority. Separate agreements specify each element's status at turnover, including which preparatory tasks the manufacturer has completed and which tasks remain to be done. Launch site facilities provide environmental and contamination control for flight hardware throughout processing.

Kennedy Space Center uses a flexible "clean pad" architecture, in which arriving flight elements move to "offline" facilities for "standalone" operations such as propellant servicing. They then go to the Vehicle Assembly Building for integration and test. "Integrated" or "online" operations in the Vehicle Assembly Building involve more than one element and define the pre-launch timeline and the critical path to launch.

The main activities in a Space Launch System launch flow are: 1, mobile launcher turnaround; 2, booster integration; 3, core stage integration; 4, stage adapter integration; 5, upper stage integration; 6, integration of the payload adapter, the fairing, and the payload (which may be, or include, an Orion); 7, integrated stack testing and closeout; 8, rollout preparations and transfer to pad; 9, launch preparations; and 10, launch. Ground systems provide power, fluids, conditioned air, and other commodities to vehicles on the pad. Hardline and radio links connect a vehicle on the pad with Launch Control, Mission Control, and the Range. Launch scrubs and technical problems may recycle the flow to a prior step. No foreseen problem would require the de-stacking of the payload (or Orion) after integration with the launch vehicle.

Secondary payloads designed for minimal impact to ground and mission operations may accompany the launch vehicle (on the Orion Spacecraft Adapter) or the Orion (in the Service Module).

Some elements of a Proving Ground mission, such as ancillary logistics carriers, may be able to fly on commercial or international launch vehicles. The providers of those launchers will process and stack flight hardware in their own facilities using their own processes, which will resemble the Space Launch System flow described above.

As launch day approaches, workers at the launch site check out the Space Launch System rocket, the Orion spacecraft, and the co-manifested payload. They integrate the flight elements in the Vehicle Assembly Building, and roll the stacked vehicle out to the launch pad, where pad crews connect the service umbilicals.

The launch team activates power supplies at the pad and ramps the output voltage up to operational levels for the umbilicals that serve each stage of the launch vehicle, the Orion Service Module, and the co-manifested element. Each stage of the rocket automatically turns on its required systems and performs system checks and maintenance. The Service Module automatically turns on required systems, performs system checks and maintenance, and transfers power to the Orion Crew Module for its own automated activation. Similarly, the co-manifested element conducts an automated activation and checkout sequence. Power usage is minimized to keep the element within thermal limits. The element maintains its low-power configuration until after trans-lunar injection, when the Orion docks to it and provides supplementary power.

After all required checkout activities are complete, the batteries in the Orion, the co-manifested element, and each stage of the rocket maintain proper charge levels using low power charge rates. Ground power remains connected throughout propellant loading.

The flight crew arrives at the launch site a few days before flight. They eat and sleep in Crew Quarters and spend their time on final training, medical examinations, circadian shifting, and other mission preparations. Quarantine protocols help protect the crew from infectious diseases.

Launch Day Activities

On the day of flight, the crew members wake up about six hours before launch. They don their suits in Crew Quarters, then ride out to the launch pad and board the spacecraft. Launch control updates the vehicle's guidance, navigation, and control system for the day's weather conditions. Power maintenance to the spacecraft continues during and after propellant loading. Just before liftoff, ground power ramps down and the Orion, the co-manifested element, and the launch vehicle's stages transition to battery power.

Launch

The Block 1B configuration of the Space Launch System uses two five-segment Solid Rocket Boosters and four Pratt & Whitney Rocketdyne RS-25D engines (modified Space Shuttle Main Engines). The RS-25Ds must reach full thrust and confirm their health before launch commit, when the hold-down posts release and the boosters ignite.

When the boosters fire, the rocket rises off the Mobile Launcher, which executes its own sequence of umbilical disconnections and retractions. Control of the mission passes over from the Launch Control Center at Kennedy Space Center to the Flight Control Room in Houston, Texas. The handover between these two authorities ensures overlapping support before and after the moment of liftoff.

The Space Launch System Engineering Support Center located in Huntsville, Alabama, supports both launch and flight operations for the rocket. The consolidated team located there supports operations from the start of countdown through disposal of the Exploration Upper Stage.

As the vehicle lifts offs, the Orion central processing units collate system health and performance information provided by all elements of the vehicle. Subsets of this data are telemetered to the ground and presented on crew displays.

Ascent

The crew monitors vehicle performance during ascent, providing command inputs when warranted. The Orion downlinks data for Mission Control during ascent, although the Exploration Upper Stage also has its own downlink ability. During first stage flight, the vehicle heads downrange, pitches down, and enters the phase of maximum dynamic pressure. Whether or not the RS-25Ds throttle down during this period is still under study. A major milestone occurs shortly after 120 seconds, when the rocket drops its two nearly-expended boosters. This event marks the end of first stage and the beginning of second stage. Booster Separation Motors direct the booster casings away from the core stage. The boosters splash down in the Atlantic Ocean and are not recovered.

With the rocket in second stage flight, the RS-25Ds gimbal to correct any transients caused by staging and to steer the vehicle on a trajectory towards the planned altitude, position, and velocity for Main Engine Cut Off. Shortly after booster separation, Orion jettisons its Launch Abort System and Service Module fairing panels.

Low Earth Orbit Operations

After the main engines shut down, the vehicle coasts toward an apogee in low Earth orbit. The Service Module deploys its solar arrays. The Orion and Exploration Upper Stage separate from the core stage at the Launch Vehicle Adapter. The Orion jettisons its star tracker covers. The Orion and Exploration Upper Stage prepare for their first scheduled maneuver: a burn to raise the orbit's perigee.

Meanwhile, the co-manifested element's thermal control system activates as soon as electric power becomes available from the solar arrays. Activation consists of enabling the heaters, starting the fluid loop pumps, adding a thermal load from the survival headers, and allowing the system to reach and maintain its setpoint. Activation should take less than an hour. After thermal system activation, the element maintains a minimum heat load (excluding heaters and external payloads) of 2.5 kW to keep the radiators from freezing.

During orbital coast, the crew members doff and stow their suits. They conduct any necessary reconfiguration of the Orion interior, such as moving stowed equipment, putting away crew seats, deploying exercise hardware, setting up science or other payload equipment, and activating the toilet in the waste and hygiene compartment.

The flight crew, with ground backup, provides Authority To Proceed for the Exploration Upper Stage to chill down its engines and execute the perigee raise maneuver, which occurs near apogee on the first orbit. Between burns, the upper stage maintains attitude control as needed to keep thermal loads within limits. After appropriate vehicle checkouts and orbital trajectory confirmation, the ground or crew authorizes the trans-lunar injection burn, which is scheduled to occur at or near the following perigee.

Trans-Lunar Injection

The 3100 m/s trans-lunar injection burn takes about eight minutes and commits the crew and spacecraft to a five-day flight to the lunar vicinity. As during ascent, the Exploration Upper Stage provides operational telemetry as well as health and status data to the Orion and to the ground through TDRSS. The upper stage also accepts commands from the Orion, and from the ground via Orion. There is no dedicated uplink to the upper stage.

Orion Separation

After trans-lunar injection, Orion maintains power with its arrays and batteries. Orion re-orients the arrays as required for undocking and docking operations. The crew installs the rendezvous and docking sensor suite onto the docking hatch, connects the appropriate cables, and performs sensor and data checks. After the crew verifies that the sensors and the docking mechanism are operating nominally, Orion can separate from the co-manifested element.

During this period, the Exploration Upper Stage maintains 3-axis stabilization in preparation for Orion separation. When commanded by Orion, the upper stage modes to free drift to prevent Attitude Control System jets from firing during separation. Orion executes separation at the interface between the Service Module and the adapter that separates it from the co-manifested element.

Co-Manifested Element Docking

Most co-manifested elements envisioned for the Proving Ground lack their own propulsion and power generation, and also have pressurized volumes that the crew must access during outbound cruise. The Orion must therefore dock with the co-manifested element while it remains on battery power and attached to the upper stage.

When separation is complete, the crew takes the controls to turn the Orion around and dock it with the co-manifested element. When the two are hard-mated, the crew can disconnect and stow the rendezvous sensors and activate survival power to the element.

At this point the crew or ground sends the command to separate the co-manifested element from the Exploration Upper Stage, which holds its attitude while the Orion maneuvers itself and the co-manifested element away to a safe distance.

The Orion then orients tail-to-sun and positions its arrays to track the sun for battery charging. When the batteries are fully charged, Orion energizes the two power channels to the co-manifested element and sends power to its bi-directional converters. The co-manifested element's systems can then be fully powered up to support crew ingress and activities. The power system remains in this transfer mode until Orion undocks late in the mission. If needed, as during a long eclipse, the co-manifested element's batteries can send power back to the Orion via the same converters.

Upper Stage Disposal

The Exploration Upper Stage disposal operation is enabled after confirmation that the co-manifested element has separated. The disposal sequence executes automatically with a time delay to ensure a safe distance between the upper stage and the Orion with its co-manifested element. In the automated disposal sequence, the upper stage uses its attitude control system and venting of residual propellant to reach a disposal trajectory that will take it to solar orbit or an impact on the Moon.

Outbound Cruise, Part 1

It takes the Orion and the co-manifested element about 5 days to reach the Moon's orbit. Command and data links with Mission Control are available through TDRSS out to ~30,000 km altitude. The Orion can also send data and receive commands through the Deep Space Network beyond ~20,000 km altitude. The Orion is out of contact with Mission Control during periods when the Moon blocks the line of sight to the Earth.

A major activity during outbound cruise is activation of the co-manifested element. The crew members don goggles and open the docking hatches. They activate basic systems and set up an air cleaner to capture any particulate manufacturing debris. Then they close the hatches for the rest of the day to allow time for the air cleaner to operate.

On the next day, access without goggles is allowed. The crew members re-open the hatches and ingress. They unfasten launch locks and activate and check out systems that are not already operating. They can unpack and configure hardware as needed. This work may include setting up crew accommodations in the co-manifested element to take advantage of its larger habitable volume.

Public communication and outreach activities, which were limited earlier in the mission because of the busy timeline, may expand during outbound cruise to include media interviews and educational events such as microgravity science demonstrations.

Lunar Gravity Assist

On the fifth or sixth day of the mission, the spacecraft performs a propulsive lunar gravity assist that directs it toward its destination orbit. The change in velocity is about 200 m/s. During this period, all hatches must be closed and the crew members must wear suits. This critical operation may consume all available crew time on the day it occurs.

Outbound Cruise, Part 2

After the lunar flyby, the crew members can doff their suits and re-open the hatches. During the five-day cruise to the destination orbit, they finish unpacking and configuring hardware in the co-manifested element. They also re-install the rendezvous and docking sensor suite on the distal hatch of the co-manifested element in preparation for docking with the small power and propulsion module. The crew may also begin preparing the interior of the co-manifested element for untended operations after Orion departs. This may include transferring any science payloads slated to remain in space until the next crew arrives. The crew members organize and stow dry trash generated during unpacking and setup of the co-manifested element, awaiting removal on a future logistics flight.

Destination Orbit Insertion

Like the lunar swingby maneuver, the destination orbit insertion burn has a magnitude of about 200 m/s. It takes place with the crew members in suits and the hatches closed. The maneuver places the Orion and its co-manifested element on a path for rendezvous with the small power and propulsion module, which was launched earlier.

Rendezvous with the Small Power and Propulsion Module

The Orion crew performs the rendezvous and docking manually with assistance from the ground. Orbital rates, gravity gradient, and eclipse frequency and duration near the apolune of the near-rectilinear orbit are all much less than in low Earth orbit, greatly simplifying rendezvous and docking operations. Following orbit insertion, the Orion S-band radio measures the target's range and range-rate and sends the data to Orion’s relative navigation filter. The mission design requires state vector resolution within approximately two hours to maintain the reference timeline. The S-band range and range-rate measurements, along with optical navigation bearing measurements, provide accurate relative navigation states within the time constraints of the mission design.

Once inside a range of about 100 km, the Orion can begin relative bearing measurements using optical navigation cameras. When the distance is less than two kilometers, the lidar instrument determines range and bearing to the target vehicle, enabling relative navigation capabilities for the transition to proximity operations. The small power and propulsion module's solar arrays may have to be feathered when the Orion is within 2 km to minimize plume effects and loads.

Within 50 m, the optical navigation cameras provide imagery that is processed to determine a relative position. At 15 m, the lidar provides a high-accuracy relative state vector, a relative position, and a relative attitude. From this point, the lidar provides continuous relative state measurement so that Orion can dock the habitat to the small power and propulsion bus.

Docking with the Small Power and Propulsion Bus

The docking mechanism is constrained by a 55° C maximum temperature difference between the passive and active halves of the mating interface, which keeps relative thermal expansion deformations within limits. The rendezvous timeline may include a hold to allow the approaching spacecraft to shade the docking interface so that the two halves meet this thermal constraint. The precise timing of the hold will be defined through analysis of the expected shadowing of the docking mechanism and the thermal environment of both halves.

During proximity operations and docking, cameras provide visual cues to enable the crew to monitor the process. The closing velocity during final approach (10 m to dock) will be less than 0.10 m/s to keep contact loads within limits.

At a range of about five meters, the Orion executes a hold while the target vehicle is commanded to free drift. The Orion crew receives confirmation of free drift from the ground and presses in for final approach. Orion modes to free drift at first contact with the docking mechanism on the target vehicle. Both vehicles remain in free drift for about 20 minutes to allow the docking mechanism to achieve a hard mate. Throughout docking operations, the performance of the mechanism and the resulting docking loads are evaluated. Preliminary analysis indicates that docking-induced torques may slew the stack as much as 90 degrees out of the desired attitude. Following hard mate, the Orion's thrusters null stack rates and place the stack in a tail-to-sun attitude. The crew members power down and stow the rendezvous and docking sensor kit. The Orion's thrusters may continue to control the stack's attitude as needed throughout the docked timeframe, or the Orion may hand off attitude control to the small power and propulsion bus.

Destination Orbit Operations

Early element delivery flights in the Proving Ground are likely to be resource-limited. The stay in the destination orbit will therefore be no longer than necessary to ensure that the new element is functioning correctly and to prepare for departure. Because time in this mission phase is constrained, no public outreach activities will be scheduled, though interior camera footage may be downlinked for later use. Destination orbit operations include routine vehicle maintenance and housekeeping tasks, and configuring onboard systems for untended operations as needed.

On the day before undocking, the crew checks out the docking mechanism and its components by issuing commands through each redundant string. The Orion terminates power transfer to the element, which subsequently receives all its power from the small power and propulsion bus. The crew members also prepare suits and tools for a possible emergency spacewalk to separate the two vehicles in case of a failure in the docking mechanism. If the spacewalk is required, it will take about one hour. The Orion breathing gas budget includes reserves for this spacewalk.

Undocking and Departure

In preparation for Orion's undocking from the co-manifested element, the crew members re-install the rendezvous sensor suite on the Orion docking hatch. They power up the sensors and perform data checks. The crew members once again don suits. Working in conjunction with the ground, they evaluate the health of both spacecraft and confirm readiness for undocking. Undocking preparations may include reorienting the solar arrays of both the Orion and the small power and propulsion bus. When the vehicle and crew are ready, Orion separates from the co-manifested element and backs away at a slow rate (less than 0.05 m/s). The crew issues commands and performs any piloting necessary to separate the two spacecraft, including a possible fly-around for photo opportunities. Once at a safe range (30-40 m), Orion may execute additional larger burns in preparation for orbit departure. After the 200 m/s orbit departure burn, the Orion orients its tail and solar arrays toward the sun, and the crew members doff their suits. They then disable power to the rendezvous sensor suite, disconnect the cables, and stow the equipment. They can also re-stow the spacewalking gear that had been deployed for undocking.

Return Cruise

The return trip to Earth takes about 13 days with a propulsive lunar gravity assist near the midpoint of the trip. As during outbound transit, the velocity change is about 200 m/s and the crew members wear pressure suits for the burn.

With no co-manifested element to work on and the mission's primary objectives achieved, the crew will have more time for other tasks. Public outreach activities during return transit will include media interviews and educational outreach events such as microgravity science demonstrations. Life science research may resume, with additional biological sampling and computer-based assessments. The crew may also carry out physical science research.

Entry and Landing

In preparation for entry, the crew members reconfigure the spacecraft interior. They set up their seats, stow onboard supplies, and collect any equipment they will carry on their persons during landing and recovery. They confirm the readiness of the life raft and other survival gear. The crew and flight controllers work together to configure the craft for entry. If the cabin pressure was reduced during the flight, entry preparations include returning the cabin to sea-level pressure on the day before entry.

On entry day, the crew members finish reconfiguring the cabin for entry, don their suits, and strap into their seats. After a final entry targeting burn, the Service Module and Crew Module dead-face the power connections between them to prepare for umbilical separation. After this point, the Service Module no longer requires power and the Command Module is powered by batteries. Separation occurs about 20 minutes before entry interface. Shortly thereafter, the Crew Module jettisons its docking mechanism. The crew members monitor spacecraft performance throughout entry, providing command inputs as needed.

The crew members continue to monitor spacecraft performance during landing, including confirmation of parachute function and splashdown. After splashdown, the crew assesses spacecraft integrity and decides whether to await normal recovery or to perform an emergency egress. After landing, the Orion electrical system is configured to a low-power crew support mode. In a nominal landing, the crew remains in the Orion until recovery personnel clear them for egress. After the crew members are safely recovered, the landing team terminates battery power to the Crew Module and brings it aboard the recovery vessel.

Knowledge Capture, Debriefing, and Process Improvement

After the mission, crews, flight controllers, engineers, and technicians record the lessons they learned for the benefit of future flights. This information informs the preparation processes for the next mission.

Untended Operations

Although the crew has returned to Earth, the spacecraft remaining in lunar orbit has plenty to do. The untended periods between crew visits provide an opportunity for further work in operations, science, and engineering. Flight controllers can develop and maintain operational experience with the vehicle. Scientists can conduct onboard experiments using internal and external instruments. Engineers can expand operating envelopes and explore different working modes of onboard equipment. The small power and propulsion bus can even take the untended stack to other lunar orbits or other destinations in near-Earth space to prove systems and reduce risks for future piloted excursions.

6. One-Year Deep Space Excursion

Another important "case study" in the Proving Ground conops is the mission that demonstrates that our systems and operational techniques are ready for a voyage to Mars. We envision a one-year excursion that takes a crew of four people outside the Earth's sphere of influence, where distance-related communication delays and bandwidth restrictions become important, where resupply is impractical, and where Orion's provisions and propulsion capability are inadequate for an early return. All of those conditions will apply during a Mars flight. The notional one-year excursion includes the first human "landing" on a near-Earth asteroid, providing valuable scientific imagery and samples, plus operational experience on low-gravity natural bodies in preparation for human exploration of Mars's moons Phobos and Deimos.

The mission begins with launch of the crew in an Orion spacecraft with a co-manifested logistics carrier that contains supplies for the long voyage. Mission planning and training, launch preparations, launch day activities, launch, ascent, low Earth orbit operations, trans-lunar injection, Orion separation, co-manifested element docking, upper stage disposal, outbound cruise, lunar gravity assist, destination orbit insertion, and rendezvous and docking with the Cislunar Transit Habitat in lunar orbit are all nearly identical to the operations described above in the pressurized element delivery mission. The one-year excursion mission breaks new ground as crew members and flight controllers prepare to leave lunar orbit.

Departure Preparations

In-space operations to prepare for a one-year trip with no resupply, restricted abort capability, and limited communication are likely to be very involved. They will include challenging tests and shakedown runs for all critical equipment on the Cislunar Transit Habitat. Extensive reconfiguration of onboard stowage may be required. Depending on the aggregate mass of the stack in lunar orbit and the specific asteroid targeted for exploration, it may not be possible to send the entire spacecraft on the excursion. The minimum set of elements is likely to consist of the large power and propulsion bus, the large habitat, the lately-arrived logistics carrier, and an element with airlock capability to support spacewalks at the asteroid. If the stack must be split, each group of elements will have to be prepared for separate operations. When preparations are nearly complete, the crew closes the hatches at the separation plane and evacuates the vestibule between them.

Excursion Vehicle Separation

At separation, either the excursion vehicle or the remaining section of the stack may serve as the active partner for undocking. The passive partner's attitude control system modes to free drift while the active partner backs away. When the vehicles are to a safe distance apart, the passive partner resumes attitude control.

Departure from Lunar Orbit

The excursion vehicle uses continuous low-thrust solar-electric propulsion to leave lunar orbit and match courses with the target asteroid. In contrast to the high-thrust systems used for all previous human exploration missions, low-thrust propulsion blurs sharp abort-mode boundaries, reduces the safety concerns that accompany cryogenic and hypergolic propellants, and spreads the risk of a major trajectory change burn across months, rather than minutes, of flight time. The normal state of an electric thruster is "on," while chemical thrusters are normally "off." Corresponding changes to flight rules and procedures will be necessary to accommodate these differences.

Orion Undocking and Disposal

The excursion crew's Orion spacecraft may accompany them on the first part of the journey. But at some point, the excursion vehicle will pass beyond the capability of the Orion to return the crew to Earth in an abort scenario, making it useless. Carrying the Orion along to serve as a crew return ship at the end of the excursion is also unwarranted: it will have exceeded its maximum certified in-space lifetime by then, and its dead weight would likely prevent the excursion vehicle from reaching its target. When the Orion is no longer useful, it undocks by remote control and enters a disposal orbit. Rapid return of the crew to Earth is now impossible, as it will be for most of a Mars mission.

Crew Activities During Transit

For most of the excursion, the ship and its crew are far from the Earth, Moon, or any other celestial body. Under constant sunlight, constant attitude, and constant thrust, the ship's systems operate in steady state. This operational mode may last for months at a time. Although the crew may not have to devote much attention to operating the spacecraft, they still have plenty to do. Below, we present a complete list of crew daily activities during transit, with estimates of duration where available. Most of these categories also apply during long stays in lunar orbit, and even during the cruise phases of Orion flights to and from the Proving Ground.

Post-Sleep and Morning Meal—Post-sleep activities include bathing, brushing teeth, changing clothes, and stowing sleeping bags. The crew may eat breakfast together or separately. International Space Station schedulers allow 1.5 hours each morning for these activities. We expect a similar allowance in the Proving Ground. If crew members have any extra time in this period, they may use it to organize schedules and prepare equipment for the day's activities.

Exercise—Aerobic and resistive exercise helps counteract the harmful effects of living in microgravity. The entire crew must share a limited set of exercise devices, so exercise is scheduled throughout the day. On the Space Station, crew members normally exercise 2.5 hours every day, unless there is an operational or medical reason to skip it. It is possible that future refinement of exercise equipment and protocols could provide Proving Ground crews with the same benefit from only 2 or even 1.5 hours of daily exercise.

Lunch—Space Station schedulers allow crews 1.0 hour at midday for lunch. In practice, crew members usually eat lunch on the go, working through their scheduled lunch break. Proving Ground crews should also get a 1-hour scheduled lunch break.

Evening Meal and Pre-Sleep—Space Station crews are allowed 2.0 hours before bed for dinner, bathing, and preparing for sleep. Antarctic field teams without rigorous schedules take longer for dinner, mostly because they cook from scratch and have to wash dishes afterward. Varied meals give psychological benefits for people in isolated and confined environments [4, 5, 6]. Proving Ground crews would benefit from extra time each day to cook (not just reheat) food. Most space crew members and Antarctic field team members wash their hands several times a day and their faces once or twice daily. They take full sponge baths every few days. Space Station crew members may use extra time during pre-sleep to write reports, prepare for the next day's work, and communicate with friends and family. They also commonly use some time in pre-sleep for recreational activities such as looking out the windows. We anticipate that Proving Ground crews will also be scheduled for 2 hours of pre-sleep activities.

Off-Duty Time—Space Station crews have little unscheduled time during the work week. They are technically off duty half of Saturday and all of Sunday, but in practice much of that time is spent working. A schedule for a long Proving Ground mission (informed by Antarctic experience) might sustainably allow 1.5 hours each work day, plus half of Saturday and all of Sunday, for personal activities. In their unscheduled time, crew members can enjoy books, music, movies, and electronic games, which have low weight and volume. Other possible activities include photography, playing musical instruments, and communicating with friends and family on Earth. Arctic and Antarctic analogs [5, 6] highlight the morale value of holiday celebrations and special meals, and the importance of separate spaces for private and group recreation.

Sleep—People must sleep about eight hours each night to maintain their health and minimize fatigue-related errors. The Proving Ground architecture provides dedicated private sleep quarters for missions longer than 30 days. Sleep shifting causes fatigue and increases the risk of crew errors, so Proving Ground mission planners will keep sleep shifting to a minimum. Key mission events driven by outside factors (such as critical high-thrust engine burns) may make sleep shifting unavoidable. When sleep shifts are necessary, they will be executed gradually, at no more than one hour per day.

System Operation—Astronauts operated the Space Shuttle through displays and controls in the crew compartment. In contrast, Mission Control operates the International Space Station remotely. A Mars mission, with communication gaps, bandwidth limitations, and speed-of-light delays, cannot succeed using the Space Station model. Looking ahead to Mars, system designs and operational concepts for the Proving Ground must work with much less human attention than the Space Station. (In fact, mastering human spaceflight operations with severely restricted communication is one of the chief goals of the Proving Ground.) The alternative to constant oversight from the ground is a local operator: either automation, or the crew. Automation is usually complicated and expensive. It adds instrumentation, mass, software, power draw, thermal loading, mission risk, and testing. Crew operation can reduce the amount of automation that must be paid for. The greatest cost savings are realized if the jobs the astronauts do are those that are easy for humans but hard for machines. During transits, Proving Ground crewmembers are likely to have time available to operate the vehicle. Based on Antarctic experience [4], each crew member might spend about 2 hours a day on systems operation. If routine daily system tasks take longer than that, they risk overwhelming the crew on days with time-consuming critical operations such as dockings or spacewalks.

Other Work—The allocations for sleep, exercise, meals and hygiene, recreation, and system operation leave about 5 hours a day for crews to do other work. Meaningful work helps people isolated and confined in monotonous surroundings to stay engaged and happy [5, 6]. The paragraphs below outline some of the crew tasks that might fall in this category.

Planned and Preventive Maintenance—Many maintenance tasks can be predicted and scheduled in advance. These include filter cleaning, surface sanitation, general housekeeping, and monitoring of onboard environment. Items needing frequent maintenance should be located in easy-to-reach places: not behind other equipment, and certainly not outside the pressure hull, where it can only be reached with a risky and time-consuming spacewalk.

Unplanned Maintenance—A chief goal of the Proving Ground is to master spacecraft maintenance concepts for a Mars mission with minimal sparing and little or no resupply. The crew will repair spacecraft systems that fail. Repair work will be more efficient if systems use common basic parts and fasteners. Systems should employ common, durable, low-risk interfaces. Equipment should be accessible: working on one subsystem should not require removal of another. To reduce the mass of the onboard tool kit, all maintenance tasks should employ a minimal set of common tools. To reduce the mass of onboard spares, crews should be able to replace a failed one-gram resistor rather than the otherwise healthy ten-kilogram unit that contains it. Maintenance on a long-duration mission should follow the example of the carpenter shop on a nineteenth-century whaling ship, with basic materials and a skilled craftsman able to repair almost anything. As in Antarctica, equipment that the crew cannot fix with the tools, skills, and supplies they have should not be sent on the mission [4]. Engineers on Earth can provide remote guidance for repair work as time permits. Onboard fault detection, isolation, and recovery software can also help mitigate system failures. Otherwise the crew members are on their own.

Scheduling and Team Coordination—All collective work requires effort to coordinate. Space crews must divide tasks among themselves, and take time to listen to instructions from, and transmit status updates to, Mission Control. On the Space Shuttle, Mission Control scheduled crew work, and most communication between crew and ground was verbal. On the Space Station, the ground still makes the schedule, but instructions and updates often travel electronically. On a deep space flight (as in Antarctica, in other space flight analogs, and increasingly on the Space Station itself), crews are likely to make their own daily schedules using electronic schedule management tools. Each morning they will review messages from the ground. The messages may include instructive photographs and possibly video. The ground may prioritize the day's work, but the crew will decide when to do each task. The prioritization scheme will include a "task list" for activities that don't have to be done on a specific day, as successfully demonstrated on the Space Station. The scheduling concept should clearly identify activities that must be done at a specific time, and activities that depend on the completion of another activity. The scheduling software should help crews limit excessive work loading and fatigue.

Science Investigations—Proving Ground crews will conduct science experiments in transit. The conditions of the flight lend themselves to investigations of microgravity biology, radiation effects, countermeasures to microgravity effects, human health and performance, and human behavior in isolated, confined, stressful conditions. Space science research is also possible. Topics may include solar physics, cosmic ray physics, the interplanetary medium, and of course the Moon (while in lunar orbit) and the asteroid that is the target of the one-year excursion.

Inventory Management—Space Station crews spend time each day managing stowed equipment and supplies, with the help of Mission Control, which maintains a database of everything stored on the vehicle. Based on Space Station experience, the Proving Ground would benefit from an inventory management system based on radio-frequency identification tags, which can automatically track the location of every item. Antarctic experience suggests that keeping the center of intelligence onboard (rather than on Earth) would improve work efficiency: crew members need not consult a stowage database if they know where they put everything. Stowage bags should be transparent so the contents are visible without opening the container. Crews will also have to manage trash. They must stow all trash where it won't interfere with work, and must control bacteria and odors in wet trash.

Medical Operations—Even if they stay healthy, crew members need periodic medical checkups and comprehensive health evaluations. For these, and for responding to illness or injury, the deep space craft needs a private "doctor's office." Proving Ground crew members will also participate in psychological monitoring and evaluation. The spacecraft will carry equipment to alert the crew (without waiting for a call from Mission Control) if solar radiation reaches levels that demand sheltering or other action.

Public Outreach—Deep space crews will participate in public outreach, mostly in the form of pre-recorded text, audio, and video messages returned to Earth. Interactive video question-and-answer sessions, popular with Space Station crews, are possible with the ~ 1 second one-way speed-of-light latency in lunar orbit, but may demand more bandwidth than the communication link can support. Interactive conversations become tedious with more than a few seconds of latency, and are impractical at a few tens of seconds.

Extra-Vehicular Activity—In lunar orbit, Proving Ground crews may conduct contingency spacewalks for emergency repairs. These operations would use the Orion crew module as an airlock, and the crew members' launch and entry suits as space suits. The crew needs this capability to respond to unforeseen problems outside the pressure hull, as demonstrated on Skylab 2 and many other space missions. On the one-year excursion, we envision multiple planned spacewalks to thoroughly explore, characterize, and sample the target asteroid. These spacewalks will require nominal airlock functionality somewhere on the stack, plus dedicated space suits (rather than modified launch-and-entry suits). Those resources would also support contingency spacewalks, should the need arise during the excursion.

Robotic Operations—Crew members in lunar orbit may teleoperate robots on the surface of the Moon. On the one-year excursion, they may teleoperate assets on the target asteroid. During times when robotic operations are infrequent, crews will maintain proficiency in their robotics skills through onboard training and simulation.

Training—On long Proving Ground missions, crews will train during the flight. They will reinforce skills learned before launch, and maintain proficiency in emergency procedures, and take "just-in-time" training for upcoming tasks and destination operations.

Asteroid Approach

Toward the end of its long transit in solar orbit, the Transit Habitat gradually approaches the target asteroid. As during lunar orbit departure, there is no discrete propulsive maneuver that can be labeled an orbit insertion burn. The final approach may take place in stages, with periods of closure alternating with periods of stationkeeping during which crew members and specialists on the ground observe the asteroid using remote sensing instruments. The observations will be used to quantify the risks of closer approach. Hazards might include electrostatically levitated dust, the presence of satellites, a rapid or chaotic rotation state, and other factors. Once the asteroid and its environment have been characterized remotely, the excursion vehicle can close to its minimum standoff distance.

Exploring the Asteroid

Notional mission timelines allow several weeks at the target asteroid. This phase of the mission will be stressing for crew members and flight controllers alike, as exploration tasks fill each day's timeline and compete with onboard systems for operator attention. The excursion crew can deploy autonomous, ground-controlled, and locally-teleoperated robots to explore the asteroid. Both free-flying and landed robots are likely. Each will carry a suite of remote sensing instruments. Landed assets will include in-situ experiments designed to gather scientific data and to thoroughly characterize the asteroid's surface environment. Some landers may collect samples and return them to the excursion spacecraft. When basic safety-related parameters are known, mission leaders can make an informed decision about whether or not to send human spacewalkers to touch the surface. We do not currently know how to conduct spacewalks on natural surfaces in milli- or micro-gravity. Personal mobility, body stabilization, anchoring, dust mitigation, scientific sample collection, and many other technical problems remain to be solved before we can confidently put humans to work on an asteroid.

Departure from the Asteroid

Orbital mechanics and the propulsion capability of the excursion stack delineate the duration of the crew's stay at the target asteroid. As the departure date approaches, the excursion crew will conduct final spacewalks to visit any remaining high-priority scientific targets, to collect equipment that may have been temporarily deployed on the asteroid surface, and to deploy instruments that will be left behind when the astronauts depart. Some of the robotic assets may be recalled and brought back to the Earth-Moon system for re-use on future missions. When departure preparations are complete, the excursion spacecraft activates its low-thrust propulsion system and gradually pulls away from the asteroid.

Return Transit

The months-long return voyage to the Earth's sphere of influence resembles the outbound transit described above.

Uncrewed Orion Flight

As the excursion vehicle approaches the Earth-Moon system, an uncrewed Orion launches to meet it. This vehicle will serve the critical function of returning the excursion crew to Earth. Its flight profile will be much like that of a crewed Orion flight, but it will probably launch without a co-manifested element. This will reduce mission risk by eliminating extra maneuvers and docking operations. It will also increase the performance margin of the launch vehicle, which might be used to direct the Orion to join the returning stack--and re-establish Earth-return capability--as early as possible. The uncrewed Orion makes a rendezvous with the excursion vehicle and docks autonomously or via teleoperation by the excursion crew.

Reuniting the Stack

The excursion vehicle enters the Moon's sphere of influence and gradually shapes its orbit to rendezvous with the portion of the Cislunar Transit Habitat stack that stayed behind in lunar orbit. The two vehicles dock, with one serving as the active and the other as the passive partner.

Crew Return

After completing any post-excursion system reconfiguration and cargo transfer (such as preparing the logistics carrier to dispose of a year's worth of trash), the crew members board the Orion for return. Their undocking and departure, return cruise, and entry and landing are all similar to the operations described above. Subjecting a crew deconditioned by many months of weightlessness to re-entry stresses at interplanetary velocities will provide valuable biomedical data for future Mars landings.

Optional Partner-Led Lunar Landing

If NASA's partner agencies have established the capability to make human excursions to the lunar surface by the time the one-year excursion mission returns, there will be an opportunity to safely quantify one of the least-understood risks of a human Mars mission: the response of deconditioned human bodies to landing on a partial-gravity body. In this optional scenario, a crew of 4 would launch to the Proving Ground on a partner-provided vehicle. They would meet the returning excursion crew and exchange two crew members. Two of the recently-launched crew members would join two of the returning long-duration crew members in the Orion and return to Earth. The other four crew members would proceed to land on the Moon. The deconditioned fliers would serve as research subjects for partial-gravity adaptation investigations. If their adaptation is difficult or slow, their "fresh" crewmates are available to take up some of their tasking.

Untended Operations

If the one-year excursion meets all of its objectives, the world's space agencies may declare that they are "Mars ready" at its conclusion. The Proving Ground spacecraft, having successfully served its primary purpose, may go on to support Mars exploration even more directly. If its systems are in good enough shape, and if its predicted lifespan is adequate, it may itself fly to Mars, where it could serve as an orbital habitat for future crews exploring the planet's moons and surface. That final mission would not carry a crew, and would require a fresh load of propellant and other servicing before departure.

7. ABORTS AND CONTINGENCY OPERATIONS

A full discussion of major failures and aborts, which will eventually comprise many books of flight rules and procedures, is beyond the scope of this paper. But a general treatment is possible here.

For unpiloted ships, the priorities are to protect human life, then to complete the mission, then to preserve expensive assets. Because the lives of the crew may depend on robotic spacecraft launched separately, those assets may launch, establish themselves in storage locations, and verify their own health before the crew is launched. A robotic ship suffering a failure on ascent may be blown up to protect civilians on the ground, or it may continue to a safe but useless orbit. Orbiting vehicles unable to complete their missions may be worth rescuing rather than replacing. Robotic ships are likely to have survival systems (e.g., body-mounted solar cells, omnidirectional antennas) and multiple layers of robust "safe-modes" to aid in recovery following a failure.

Spacecraft carrying humans have the same priorities, complicated by the presence of the crew on board. Ascent aborts must protect both the crew and the public. The crew and ground will verify critical systems before each major mission step, especially trans-lunar injection, after which a quick return to Earth becomes difficult or impossible. A decision to land on the Moon is a similarly important risk milestone. Piloted ships will carry reserves of life-support consumables in case a major burn, rendezvous, or mission element fails, forcing the crew to wait days for another opportunity.

The following paragraphs outline some specific aborts and contingency operations relevant to the Proving Ground.

Emergency Egress on the Launch Pad

If an emergency demands evacuation of the launch pad, an egress system rapidly transports personnel from the spacecraft access level to a safe haven protected from fire, fumes, and blast. The safe haven is stocked with essential survival gear including breathing air, water, and food. It provides first aid kits, communications equipment, and suit cooling to sustain the evacuees if rescue is delayed. The arriving rescue team decontaminates personnel as required and transports them to a triage site for medical treatment and stabilization. If necessary, emergency evacuation to a hospital is possible.

Pad Abort

In a catastrophe that prevents a safe pad egress, the Orion can abort by activating the Launch Abort System, which fires to carry the Crew Module away from the pad. Either a manual or an automatic command can trigger the abort. Pad abort is available after the Launch Abort System is armed and the

Crew Access Arm is retracted to the "Park" position. Pad abort is no longer possible after first motion.

In a pad abort, the abort system propels the Crew Module to the east for a water landing. Aircraft and pararescue teams aid the flight crew after landing. Pararescue personnel deploy from the aircraft and provide medical care for the crew while in the water. Helicopters pick up the crew and pararescue team, and transport injured crewmembers directly to a hospital or to a specified triage site, depending on the severity of the injuries.

Strong onshore winds can carry the Crew Module back across the shoreline to touch down on land. In this case, Kennedy Space Center Fire-Rescue personnel meet the crew at the landing point. If the astronauts are unable to egress the Crew Module themselves, the Fire-Rescue team assists them. The Fire-Rescue team decontaminates the crew if necessary, then transports them to a triage site for medical treatment and stabilization. Helicopters are available to evacuated injured personnel to a hospital if necessary.

Orion Cabin Depressurization

If the Orion suffers an unrecoverable cabin leak, it can still provide life support for the crew. Onboard systems, Mission Control, or the crew members themselves may detect the decrease in cabin pressure. Once alerted to the leak, the astronauts rapidly don their suits and configure them for pressurized intra-vehicular survival. Meanwhile, the Orion introduces gas into the cabin in an attempt to maintain a habitable pressure. Once the crew members are suited, the Orion starts a controlled depressurization to vacuum (in accordance with a prescribed pre-breathe protocol, if possible). After the pre-breathe interval, the crew members can reduce their suit pressure for better mobility. The Orion and the suit provide oxygen and remove carbon dioxide during the return trip to Earth.

For missions within the Earth's sphere of influence, the time from the cabin depressurization to Earth return can be as short as a few hours or as long as several days. (Precise abort durations will be a product of future work.) Remaining in a pressurized suit for days with minimal water and no food or waste removal involves considerable discomfort and health risk. The goal of this scenario is not to provide a pleasant journey, but to return the crew members to Earth alive after what would otherwise be a fatal mishap.

Orion Auxiliary Return from the Lunar Vicinity

If the Orion's main engine fails, the spacecraft can still return to Earth using its auxiliary engines. These smaller engines are less capable, so the resulting Earth return trajectory may take longer. This scenario drives the amount of crew provisions that the Orion must carry.

Crew Rescue after an Off-Nominal Landing

In an emergency, the Orion Crew Module may arrive at its planned landing site before a recovery team is in place there. Alternatively, it could land in a remote location where recovery is more difficult. After an off-nominal landing, ground rescue teams and Mission Control work together to rescue the crew and retrieve the Crew Module. After landing, the Crew Module provides the crew with survival and communications capability for 24 hours. It also transmits its location for at least 24 hours after landing. Rescue personnel can reach the crew within 24 hours of splashdown at a pre-designated emergency landing site.

After an off-nominal landing, the Crew Module safes itself as it does after a normal landing. The crew members stay inside with the hatch closed and wait for the rescue team to arrive. If conditions force them to leave the Crew Module, they gather emergency survival equipment, open the hatch, and egress.

Ascent Abort

Four classes of malfunction may cause an ascent abort: propulsion failure, loss of control, structural failure, and system malfunctions which prevent the Orion from reaching orbit or sustaining operations there. Different abort modes apply depending on the nature of the problem and the conditions of flight. Ascent abort coverage begins at first motion and ends when the vehicle achieves a stable orbit.

The crew, Mission Control, and automatic onboard systems can initiate ascent aborts. The crew can enable and inhibit automatic aborts, except for those triggered by the flight termination system, which are always enabled. The launch vehicle monitors a set of abort trigger conditions. If any are reached, the launch vehicle automatically transmits an abort recommendation to the Orion on a dedicated link. The Orion monitors its own abort triggers, and those of any additional propulsive elements.

When an abort is triggered, the Orion selects an abort mode and sends the appropriate commands to the launch vehicle. The two elements coordinate their actions, including main engine shutdown, Orion separation, and Launch Abort System or Service Module ignition, to provide the best chance for a successful abort.

Range Safety monitors rocket launches and, when necessary, sends flight termination commands to prevent vehicles from passing impact limit lines beyond which falling debris could threaten the public. Range Safety transmits commands directly to the flight termination system in the launch vehicle and other propulsive elements. If an Orion is present, the flight termination system in the propulsive element sends it a signal to initiate an abort, and the destruct system incorporates a delay to allow the Orion to escape from the rocket.

After an ascent abort and ocean landing, aircraft and pararescue teams find the Crew Module and aid the flight crew. Pararescue personnel deploy from the aircraft and provide medical care for the crew while in the water. Helicopters pick up the crew and pararescue team, then transport injured personnel directly to a hospital or to a specified triage site, depending on the nature of the injuries.

An engine failure (or other problem, usually related to propulsion) late in ascent may trigger an Abort To Orbit. Such failures almost always cause the loss of major mission objectives. This abort mode maximizes the performance of propulsive elements to achieve a low but safe orbit, providing hours (rather than minutes) for the operations team to assess options and optimize re-entry plans. It is also safer for the crew than landing in a remote part of the ocean.

Aborts from Deep Space and Lunar Excursions

Abort options for expediting a return to Earth from deep space, for returning to lunar orbit after a refused landing on the Moon, or for reaching an off-nominal orbit after a failure during ascent from the Moon, are the subject of future work. Many of these options will be severely constrained by propulsion limitations. The long travel times needed for Earth return (days or weeks from the lunar vicinity, months for deep space) and severe restrictions on vehicle mass (and hence system redundancy and inventories of spare parts) will further complicate deep space abort planning.

Onboard Repairs

The Orion spacecraft has a limited set of tools that the crew can use for basic in-flight repairs. The Cislunar Transit Habitat carries additional tools plus a small inventory of spare parts, allowing crew members to respond to more, and more serious, failures. If a repairable malfunction occurs while the stack is unoccupied, the next crew or cargo flight might bring dedicated tools and spares to fix that specific problem. Despite these repair capabilities, most serious system failures that happen while a crew is on board will probably result in early mission termination.

Degraded Capability

If a failure can't be repaired and doesn't threaten crew safety, the flight may continue with degraded capability. Mission objectives affected by the failed system may be lost, but others may still be achieved.

Use of the Habitat as a Safe Haven

If an Orion spacecraft suffers a major failure that makes it uninhabitable or unfit for Earth return, the crew can use the Cislunar Transit Habitat as a safe haven to wait for a rescue vehicle from Earth. Depending on the specific malfunction, the crew may or may not be able to leave the Orion hatch open and use the Orion for habitation or other purposes. If the Cislunar Transit Habitat has airlock capability, the crew may conduct spacewalks to repair the Orion, or to manually separate a completely dead Orion from the stack. If the wait will be very long, one or more additional logistics carriers may fly to the Cislunar Transit Habitat with supplementary oxygen, water, food, and other supplies. Some mission activities might continue during safe haven operations.

Use of the Orion as a Safe Haven

If the Cislunar Transit Habitat suffers a malfunction that makes it uninhabitable, the crew can abandon it and retreat to the Orion spacecraft. The Orion can serve as an airlock for spacewalking astronauts to attempt to repair the habitat. A more likely course of action is for the Orion to undock from the habitat and return to Earth. If the transit time for Earth return exceeds Orion's capability for crew support, and if a logistics carrier is present at the Cislunar Transit Habitat, then both vehicles might undock and then dock with each other to provide the crew with additional supplies and habitable volume for Earth return.

8. SUMMARY AND CONCLUSION

In this paper, we have outlined the concept of operations for a Proving Ground near the Moon or in high lunar orbit. The centerpiece of the Proving Ground is a Cislunar Transit Habitat. The conops outlines the flight and ground elements that make up the Proving Ground architecture. It summarizes the missions that construct, use, and relocate the Cislunar Transit Habitat, and presents detailed operational sequences for a representative subset of those missions. It discusses some aspects of aborts and contingency operations.

The conops is one of several major products from the first year of the Proving Ground study. Others include top-level requirements, mission objectives, and technical descriptions of the architecture's flight elements. All of these products will continue to evolve as the study moves into its second year. Key areas of future work include tighter integration between NASA and other national space agencies to create a space exploration architecture that provides compelling benefits for all who wish to invest in it, and better cooperation between the Proving Ground and other existing and planned programs such as the International Space Station and the Evolvable Mars Campaign [1].

We hope that our work will lead to human space flight missions that can close the substantial gap between today's human space flight operations with the International Space Station, 400 km from the Earth, and future flights a million times deeper into space to reach the planet Mars.

ACKNOWLEDGEMENTS

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BIOGRAPHY

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